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Requirements for Increased Ground Mobility

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IT WOULD SEEM on the surface that it should be absurdly simple to specify the mobility required by our modern day Army. Obviously, we need our vehicles to possess as much off-road performance as can be built into them. Unfortunately, this simple proposition is not necessarily true nor is it a simple task to qualify the statement. It is not true because the off-road mobility may be secured by a total compromise of other important vehicle characteristics. It is not easy to qualify the "amount" of mobility because we do not have a complete knowledge of the terrain environment in which a particular vehicle is to live. Furthermore, we do not have any complete agreement as to the method of measuring the off-road performance of a vehicle.

The lack of a generally accepted standard measure of mobility is directly related to the very complex set of topics covered by the word mobility. A rather hopeless search for a mobility index or number has resulted in much lost time and effort but has not produced a simple, convenient, description of vehicle mobility; and indeed it cannot be because a proper definition of vehicle mobility is a complex combination of terrain-vehicle relationship that may be, at best, manageable by Operations Research techniques. The magic "mobility number" will be the result of a lengthy matrix computation as suggested by Bekker in his second book (1).*

Before examining the increase in ground mobility that is required, it would seem useful to establish where we stand today. Lacking a complete description of vehicle off-road

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*Numbers in parenthese designate References at end of paper.

performance, an attractive means of identifying the current state of vehicle mobility is to look at the elements of performance of field units which depend on vehicle mobility. A reasonable gauge of either the value or the effect of vehicle mobility on the operation of a military unit is the average speed which the unit can achieve in its maneuvering. Static situations are not chosen in combat so that the primary reason for increasing vehicle ground mobility is to increase the rate of movement of a military unit. If an increase in overall vehicle mobility does not produce either a great reduction in the effort to achieve a given rate of movement or a significant increase in the rate, there is little justification in concerning ourselves with the mobility problem.

It is rather dismaying to look at the rate of major military movements over the past several thousand years. If the span is taken between Caesar and Patton, what do we find? We find that Caesar moved his Legions at a rate of 12 miles a day. He was confined largely to infantry so was not encumbered with lengthy support trains. Napoleon achieved similar rates with the advantage of a larger animal population to assist in hauling his equipment. We find essentially the same rate of movement during the American Revolutionary War and the Civil War. And finally, Patton, in his dash across France, averaged 12 miles a day (2). His slow rate of advance is defended as resulting from a lack of fuel and supplies, not vehicle mobility. Precisely the point we started from: if an increase in vehicle mobility is to be useful, it must result in some noticeable effect, either on the rate of advance or the ease of advance. The support required to keep Patton going was certainly several orders of magnitude greater than required by Caesar. Overall, he was not capable of moving significantly faster. The fact that he

ABSTRACT

The current mobility available to tactical units is discussed and the problems surrounding the specific requirements and the determination of vehicle performance are presented. Mobility is broken down into seven elements and the method for specifying each element is presented. A complete discussion of the soft soil performance is reviewed and future mobility requirements are offered in general terms.

had more mobile machines than did Napoleon did not permit Patton to move at a significantly higher rate because the problem of "supporting" his machines was so great that he achieved little net gain.

Obviously, these samples were selected to support the thesis advanced. I do not for a moment recommend going back to Caesar's operations nor do I think that the above discussion can be taken to indicate a futility in achieving increased ground mobility. The purpose in presenting the rather discouraging picture was to indicate that mobility is not useful as a goal in itself: but rather as an effect on military operations.

To return to the earlier stated desire to establish where we stand today: concerning mobility, it would seem that the current vehicles do not provide the combat unit with the mobility that they require. The cost of achieving a modest rate of movement is not reasonable and there are too many terrain conditions that deny vehicular movement. We ask that our vehicles operate in all conceivable terrain conditions but are fully confident that they would be useless in the jungle, polar wastes, or muskeg. Because of the current emphasis on all phases of mobility at almost all levels of Research and Development management, it is rather obvious that our current vehicles are considered to have marginal performance for present tactics and inadequate performance for future requirements. For example, a recent study was made by the Transportation Corps (3) in which they concluded that the complete gambit of tactical vehicles are not adequate for them to properly perform their mission.

If we consider present tactics as including World War II, a complete freedom of movement could very likely have had a massive effect on the outcome of that conflict. The German operations in Eastern Europe and Russia could well have been a different story if their vehicles had not been almost totally incapable of coping with the mud. Or if they had been permitted use of the bogs on their left flank in Poland they would have had a considerable tactical advantage.

As a general thesis, if increased soft ground mobility is not accompanied by a compromise that off-sets the gain, any increase in mobility over that of a potential or actual enemy is a very real weapon. If we can use terrain that is denied the enemy because his vehicles cannot negotiate the obstacle, we then can attack him with weapons that he cannot match. In effect, our superior mobility permits us to fight a modern war while the enemy is forced to fight a Napoleonic war.

The nuclear battlefield imposed a greater requirement for mobility and, in particular, high off-road speed. The tactics for nuclear war force extreme dispersion of troops and do not permit concentrations of even dispersed units. If we double or triple the area that a unit is required to hold, we find that the more process of living, that is, communication and logistic support, requires either much higher speeds or many more vehicles. It is obvious that we do not have to increase the unit area of responsibility by many factors before we reach the point, in which our current vehicles can do no more than maintain life in a static situation. If we are expected to live and fight a fluid battle the surplus energy must come from improved mobility. But, without even considering the problems of the future conventional or nuclear battlefield, we still have the problem of today's mobility.

How have we arrived at a situation in 1962 in which neither our combat nor our logistic vehicles have sufficient off-road mobility to permit the application of current tactical doctrine? In my opinion, we have arrived by an inability to specify what our needs are in terms that industry or we ourselves can translate into design concepts. Our requirements "Military Characteristics" have been stated in vague, qualitative, generalities. To quote from a recent vehicle requirement: The vehicle must "be capable of all-season, on-road and off-road operations, over various types of difficult terrain to include mud, sand, soft marches, jungle swamps, muskeg, deep snow, and tundra; and be capable of crossing vertical obstacles as high as possible, consistent with aspects of the design." When a statement like this is taken out and hung up for the neighbors to see, I admit that we blush. Before you representatives of industry sit back and agree that this is what you have been saying all the time, I would like to point out that neither the farmer nor the construction industry have offered any better guidance in specifying their requirements. The problem facing the military, the farmer or construction man is the same: there has not been a means available to specify requirements nor to examine the relationships between the vehicle and the soil.

In order to examine this situation and the possible solution, it is useful to attempt a rough breakdown of the elements comprising off-road mobility. A reasonable description of off-road mobility consists of these elements:

1. Soft ground performance.
2. Obstacle performance.
3. Rough ground speed.
4. Water operation.
5. Maneuverability and agility.
6. Slope performance.
7. Air transportability.

If we look at these elements, most of them appear quite manageable and amenable to specifying quantatively. Obstacle performance can be specified requiring that the vehicle negotiate a vertical wall of stated dimensions, or a ditch, bump, or other obstacle that can be established by stating its geometry.

The rough ground speed can be specified by requiring a minimum speed over a standard, reproducible course. Or the course can be described by stating a geometric profile that can be handled in an analytical evaluation. In any event, the performance required can be specified exactly rather than by a vague requirement that it "Be capable of sustained operation . . . with correspondingly lower speed capability on less advantageous surfaces."

To specify water performance we can require an ability to attain a minimum speed and to climb out of a "stated" representative bank. The geometry of the bank can be def-

initely stated but the soil conditions of the bank would be difficult to establish. However, at least a major portion of the water performance can be stated in numbers.

The maneuverability and agility of the vehicle is considerably more difficult to specify because these terms are rather vague. However, it seems possible to describe our requirements if we put ourselves to it. We can specify turning radii, the ability to negotiate a circuitous route, the ability to accomplish turns with a stated minimum loss of forward speed. The agility is a vague term that can perhaps be best satisfied by attaching minimum speed requirements to the elements comprising maneuverability.

Slope performance has been stated quantitively for years. However, the condition of the surface of the slope has been left an open issue. If slope performance is specified to establish power, braking levels, and the stability, there is no particular need to specify the surface condition. If, on the other hand, we wish to establish a capability in a vehicle to negotiate a 60% slope in nature, then the soil must be specified. If it only tells us that the vehicle had adequate power to climb the hill, a fact which can be established by a drawbar-pull test, then slope requirement is of little use, so let's not bother with that type of specification and instead demand a minimum power level. I am sure that we are really interested in establishing an ability to climb a natural slope so that both the per cent slope, and the soil type and condition should be specified. The side slope performance requirement is straightforward and seems quite adequately specified in its present form.

Air transportability is patently simple to specify: we know both the weight and size restrictions and can without any further ado state them. Current practice seems to be to specify that the vehicle must be transportable by a class of fixed wing aircraft or helicopter. This would be fine if the classifications did not change with improvement in the state-of-the-art of cargo aircraft.

All of the above suggestions could have been implemented years ago and a major portion of military vehicle characteristics could have been specified exactly. However, even though the vague generalizations would have been removed from these factors, the problem of specifying soft ground performance exactly would have remained.

The development of a means to specify vehicle requirements for soft ground performance is parallel with the development of a system of soil-value relationships. There have been several approaches taken to the study of vehicle mobility, but the work of Bekker (4) is the most general and, therefore, the most useful.

The approach that Bekker has taken is very straightforward. He measures the properties of soil and relates the vehicle characteristics to the soil properties through equations written on the basis of conventional mechanics. In general, he has reduced the problem of a wheel or track moving in soil into two parts: traction effort and motion resistance. This has dictated two soil tests since tractive effort is associated with soil shearing strength and motion resistance with bearing strength. I hesitate to use the term "bearing" since

bearing capacity has a very specific meaning to civil engineers. The bearing strength referred to here is the resistance the soil offers to the penetration of a plate, wheel, track, or other load.

The soil tests consist of obtaining force-deformation curves from a sinkage test and from a shear test. The resulting curves are fitted with equations that include parameters that Bekker has chosen to call "soil values." A set of soil values constitutes a description of the strength characteristics of a particular soil. Bekker derived equations for the force-deformation curves in which seven soil values appear. Others (5) have suggested the use of a six value system which will be discussed at the appropriate point.

In the Bekker system, the vertical force-deformation, or sinkage, curve is represented by the equation:

$$p = (\frac{k_c}{b} + k_\phi) z^n \qquad (1)$$

where:

k_c, k_ϕ and n = Soil values

p = Pressure

z = Sinkage

b = Lesser dimension of a rectangular loading area or radius of a circular loading area

Originally, k_c and k_ϕ were referred to as moduli of deformation due to cohesion and friction, respectively. These notations assisted in discussing the soil value system but had the disadvantage of implying a physical significance to the values which did not exist. For example, if the values had the physical significance implied, a purely frictional soil would arbitrarily receive a zero value for k_c. However, test results produce nonzero values for k_c, and sometimes large negative values. If one assumed zero for one of the soil values and reduced the force-deformation curves on that assumption, it is obvious that an incorrect description of the soil characteristics would likely result.

A schematic drawing of the apparatus for conducting a sinkage test is shown in Fig. 1. In order to obtain the values k_c, k_ϕ, and n, at least two plates of different size must be used and two sinkage curves obtained. The plates should be as large as soil conditions permit, and experience indicates that a minimum size is of the order of 4 in. diameter for a circular plate or 4 in. width for a rectangular plate. As a minimum, the difference in plate sizes should be at least 1 in. in either radius or width. These plate sizes are not always possible to use due to strong soil conditions, but should be met as well as conditions permit. In order to extract the soil values from the sinkage curves, the curves are replotted on log-log paper so that we have
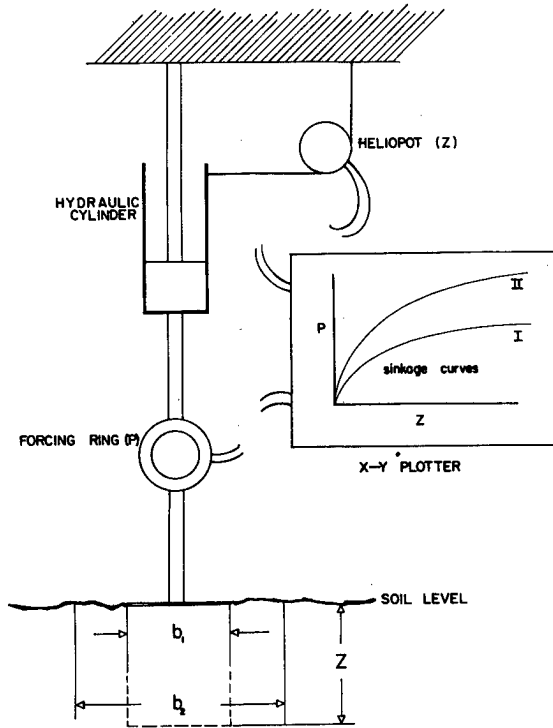
Fig. 1 - Schematic of apparatus for conducting a sinkage test

$$\ell n \; p_1 = (\frac{k_c}{b_1} + k_\phi) + n \ln z_1 \qquad (2a)$$

$$\ell n \; p_2 = (\frac{k_c}{b_2} + k_\phi) + n \ln z_2 \qquad (2b)$$

By selecting the intercepts for $z_1 = z_2 = 1$ then

$$\ell n \; p_1 = \ell n \; (\frac{k_c}{b_1} + k_\phi) = a_1 \qquad (3a)$$

$$\ell n \; p_2 = \ell n \; (\frac{k_c}{b_2} + k_\phi) = a_2 \qquad (3b)$$

where:

a_1 and a_2 = Intercept values

Algebraic solutions for k_c and k_ϕ gives

$$k_\phi = (a_2 b_2 - a_1 b_1)/(b_2 - b_1) \qquad (4)$$

$$k_c = (a_1 - a_2) (b_1 b_2 / (b_2 - b_1)) \qquad (5)$$

The n value can be obtained from the slope of the curves plotted directly on log-log paper. The resulting soil values permit computations to determine the sinkage of a plate, wheel, track, or other reasonably shaped load. Since the motion resistance of a wheel or track is proportional to sinkage, the sinkage computations serve as a basis to predict the motion resistance of the vehicle.

The horizontal force-determination or shear curve was represented by Bekker with the equation:

$$S = \frac{c + p \tan \phi}{y_{max}} e^{(-k_2 + k_2^2 - 1)k_1 d}$$

$$- e^{-(k_2 - k_2^2 - 1)k_1 d} \qquad (6)$$

This equation is an extension of the Coulomb's equation $s = c + p \tan \phi$, which describes the relationship between maximum soil shear strength, s, cohesion c, normal load p, and friction angle ϕ. In Bekker's equation, s, c, p, and ϕ have the same meaning but he has modified the equation with the additional parameters k_1, k_2 and d to describe the complete force deformation curve rather than the maximum value. The factor y_{max} is the maximum value of the exponential expression inside the brackets. The factor d is introduced to define the deformation at any point on the curve that is of interest. The parameters c, ϕ, k_1 and k_2 are the shear soil values. Before providing a brief description of the method of obtaining these values, the desirability of describing the complete shear curve should be defended.

The shear curve tells us how much tractive effort a wheel or track can extract from the soil. If we have a soil which develops shear curves similar to those shown in Fig. 2(A) the soil must receive a considerable deformation before the maximum tractive force is achieved. For example, if this deformation is 2 in. and we are concerned with a wheel which is only causing a 1 in. deformation, we obviously are not interested in the maximum tractive effort, but with that for the 1 in. point. If we are to be able to compute values of tractive effort other than maximums, we must describe the complete shear curve.

Fig. 2 is a schematic of the device to measure the shear curve for soils. The shear head consists of an annulus in order to simplify the boundary conditions of the test and cause shearing of the soil without "bull dozing," as would occur if a rectangular plate were used. This test consists of the application of a known normal load and the measurement of torque required to rotate the shear head. By conducting several such tests with different normal loads, a series of curves are obtained. The maximum value of each of these curves for each pressure is plotted in Fig. 2(B), and the values of c and ϕ can be obtained directly. The values of k_1 and k_2 are quite troublesome to obtain and a graphical solution has been developed which is adequately described elsewhere (1).
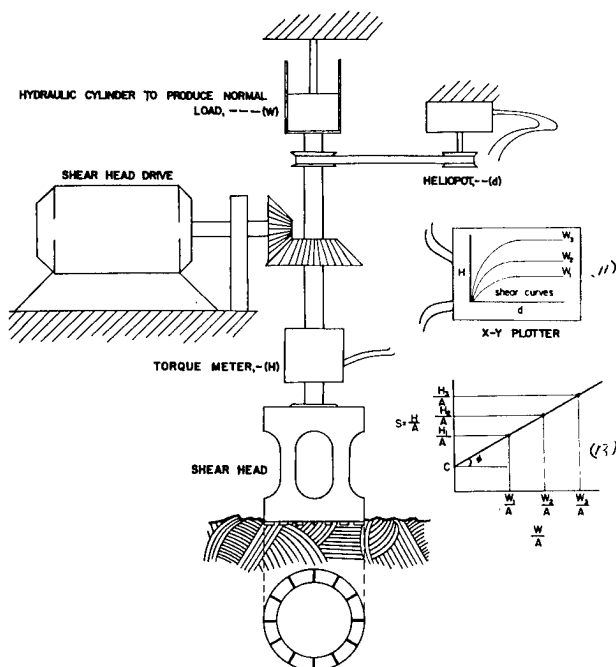
Fig. 2 - Schematic of device to measure the shear curve for soils

Fig. 3 - Evaluation of "K" from typical shear stress-strain curve

Janosi (5), among others, recommended a reduction of the shear soil values to c, ϕ, and k by describing the shear curve with the equation:

$$s = (c + p \tan \phi)(1 - e^{-i/k}) \qquad (7)$$

in which he has called "k" modulus of deformation. The value is quite simple to obtain, as is shown in Fig. 3.

With the development of a means to describe soil strength properties that are of importance to the operation of vehicles, it is now possible to relate the vehicle to the soil. I shall not present any examples of the equations that have been developed because they have been described repeatedly in publications of the Land Locomotion Laboratory. The form of Eqs. 1, 6, or 7, produces difficult arithmetic manipulations but the application of the soil value system in the soil-vehicle relationships is completely analogous to the strength of materials. Where we use the neat Hooke's Law in strength of materials, we use the horizontal and vertical force-deformation curves in land locomotion mechanics.

In order to determine the motion resistance of a wheel, for example, the work taken to move an area equivalent to the wheel contact area through a sinkage z against the pressure p is taken to comprise most of the motion resistance. The only complication that arises is that both the contact area and the pressure vary with sinkage, and Eq. 1 is introduced to account for the variation in pressure. Since this equation has an exponent that is a variable, the result is some ill-behaved integrals that are solved either by approximate methods or by computer.
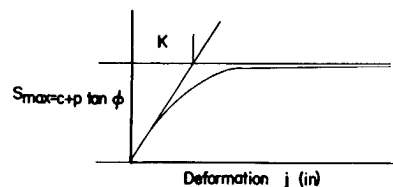
If the development of a family of equations is to be of more than academic interest, they must have some practical application. If we are to use the equations to predict vehicle performance, for example, we are vitally interested in the accuracy of the predictions. Experience has indicated that the accuracy of predicted vehicle performance is closely related to the degree with which experimental conditions agree with the assumptions made in predicting performances. Fig. 4 represents results of predicted and experimental vehicle performance made by Harrison (6). In this particular case, Harrison was able to control test conditions to closely approximate his assumptions and the agreement between predicted and experimental results is certainly adequate. On the other hand, Czako (7) predicted the performance of a series of vehicles that were operating under field conditions in sand with little control possible. His predictions of the values for the drawbar pull-weight ratios was quite bad, but the order of performance that he predicted was satisfactory. In the case of all the wheeled vehicles, the predicted performance was much higher than the actual performance. Most of his errors can be accounted for by the fact that actual wheel sinkage was much greater than the predicted value. The source of this error lies with the fact that the equation at present does not include the effect of the slip-sinkage relationship. In granular soils in particular, the dynamic sinkage is much greater than the static sinkage. Since motion resistance, in any case, is a function of dynamic sinkage, a definite error enters when static sinkages are used in the computations. The aggressive tread on the military tire is an additional source of error. The aggressive tread tends to cause a much greater disturbance to the soil than does a smooth tire. Indeed, this is why the tread is selected. However, for sand operation, the aggressive tread deteriorates performance because greater sinkage for a given slip condition results with no associated increase in tractive effort.

Other sources of error can be found in the assumption made by Czako in his computations. For example, he measured the properties of the sand and established a mean value for the soil strength parameters. He then used these mean values to predict performance. If the wheeled vehicles did not have locking differentials, it would seem more realistic to assume that at least two of the wheels would be operating in the weaker soil conditions, and thus the lower soil strength should be taken as governing performance.
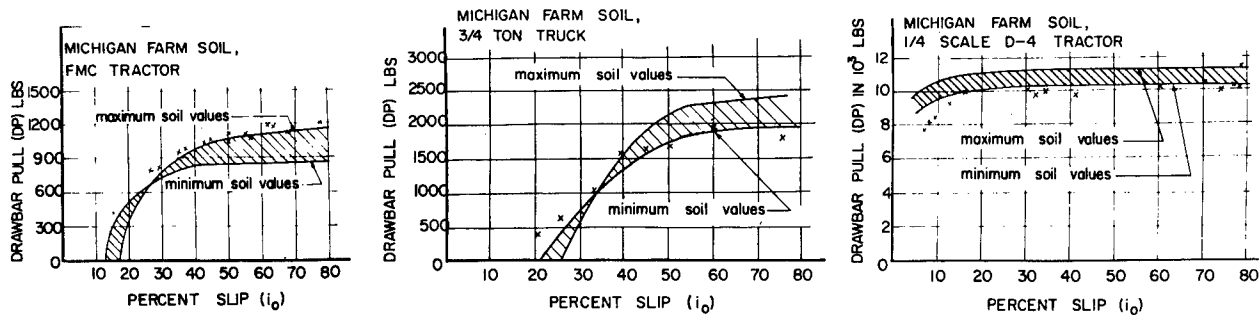
Fig. 4 - Results of predicted and experimental vehicle per-
formance made by Harrison (Ref. 6)

In at least three cases, the wheeled vehicles were not
capable of developing maximum drawbar-pull due to "bounc-
ing." As the drawbar-pull load was applied, the vehicles
began to bounce rather badly, rather than settling down nicely
and pulling.

His predictions of the performance of the tracked vehicles
was correct both for order of merit and absolute value. Since
the tracked vehicles can be forced to develop maximum
tractive effort on both tracks, his assumptions were satisfied.
In addition, the problem of describing the behavior of a track
operating in deformable soil is much simpler than for a
wheel. The ratio of tractive effort to motion resistance is
sufficiently high so that a large error in computing motion
resistance has little effect on the results.

You may well feel that I have wandered far afield from
the stated objective of this discussion, since the subject was
supposed to be concerned with the requirements for increased
ground mobility. I submit that the first step in stating re-
quirements is to establish some means of describing the item
for which the requirements are desired. You would never
negotiate for an electric motor based solely on the moisture,
temperature, or explosive atmosphere in which it was to op-
erate. You would look first at the performance requirements
and then specify the special characteristics desired. The
purpose of this is to indicate that we can now describe the
performance that we must have for our vehicles.

However, it is not quite this clearcut. We can indeed
describe the performance that we require and we can do this
in terms of numbers, numbers that you can evaluate against
your concept. We know how to describe soil properties with
reasonable accuracy, and we can predict or evaluate the
performance of vehicle concepts. What we cannot do is
specify the range of soil conditions that are significant to
vehicle performance. What must be done next is to measure
the properties of as many soil conditions as possible so that
the frequency of occurrence of weak soils can be established
and the importance of the performance in weak soils evalu-
ated. It may well be that the user will be adamant in his
demand for a maximum ability to negotiate weak soils;
however, he will be able to determine how much the soft
soil performance will cost him.

Now, to attempt to be as specific as possible, the mo-
bility requirements will be set down. The starting point
must be to accept aerial delivery as a fact of life. With
this, we must also accept small, light weight machines as
the general configuration that must evolve. If small, light
weight vehicles are to be useful, they must be capable of
operation as a unit in a multiunit vehicle. It doesn't make
good sense, for example, to place a sacred upperbound to
vehicle load carrying capacity since logistics are not ame-
nable to regulation. If, for example, logistical requirements
dictate a capability to move 15 ton loads, we can either
demand a single vehicle with a 15 ton payload or we can
accept a three unit vehicle comprised of three 5 ton payload
units. Since aerial delivery limits size, the only reasonable
direction is for multiunit configuration.

If conventional delivery of artillery and tank gun rounds
is not to be abandoned altogether, combat vehicles will also
have to be designed in multiunit configurations. Again,
aerial delivery dictates the articulated form since a weight
limitation is imposed. One may argue that we need only
develop bigger cargo aircraft, and tanks become transport-
able. However, aircraft follow the same physical laws as
any other body, and they face the same problem of mass in-
creasing by the cube power and area by the square power.
It becomes very attractive, then, to attempt aerial delivery
of combat vehicles by making the vehicles air transportable
rather than by making the aircraft capable of transporting
the combat vehicles.

Without doubt, future vehicles must be, as a minimum,
capable of floating and, if possible, swimming. However, in
addition, a percentage of the vehicles must be equipped with
a means to negotiate river banks. It does us little good if
all of our vehicles can float if we find that they float, and
float, and float, but never get out of the river. It also does
us little good if the engineers must prepare vehicle exits for
river crossings, since they might just as will build a bridge
at the outset. Of more significance is the fact that our aerial
delivered force won't have much of the massive bridging
equipment currently available, since aircraft won't be ca-
pable of delivering it unless the airplane itself happens to
flop into a river by accident at an opportune spot.

An additional requirement that must be met will be the provision of a winch, capstan, or other device, that will permit an individual vehicle to extricate itself from all but the most extreme situations. Due to the problem of aerial delivery, heavy equipment will not be available to recover immobilized vehicles so that two alternatives present themselves: abandon the vehicle or provide a means for self-recovery.

A solution must be found to permit operation of vehicles at much higher speeds than are presently possible. Current and future tactics assume a freedom of movement and operational speeds off-road that we simply do not have and cannot provide with conventional suspensions. Low spring rates and extremely large wheel travel must somehow be made compatible with highway operation and the requirements of firing stability. We don't need theoretical guidance in the problem of high off-road speed since it has been available for a long time: we need hardware. Once we have achieved the improvements already possible within the state-of-the-art, we then need to turn to our theorists for the next step.

A major increase in the weak soil performance is required and this can be only obtained through a proper design approach. The starting point for any vehicle concept must be the relationship between the vehicle and the soil. It means nothing whatever if we utilize perfect engines, transmissions, fire control, or whatever your pleasure, if the wheel is too small or the axle load too great, or if the track is improperly proportioned. A very real problem associated with good weak soil performance is that the machines that are designed for this specific characteristic appear to be much too large. This is a fact of mobility life to which we will have to become accustomed.

Vehicles capable of operation in areas which are currently total obstacles are required. For example, operation in muskeg or tundra has been considered as nearly impossible. The stress of economics has forced both pulp and oil companies to operate in this environment and they have been successful. Admittedly, the machines that they have caused to be developed would not perform very well in the desert. Since these machines were developed for a specific environment, there is no more reason to expect them to operate well in totally different environment than to expect a refrigerator to make an efficient heat source. Admittedly, the refrigerator will develop a net heat input into a home, but it is a very poor approach to heating. The point I am attempting to make is that special environmental area vehicles will not only be acceptable, they are required. The search for a universal vehicle has been accepted as impossible of attainment. I don't for the moment want to imply that we should have an unlimited series of vehicles: I do want to imply that a vehicle designed for operation in muskeg, swamps and tundra, and not the desert and Arctic as well, is no longer an anethema.

In conclusion, to summarize the points in this discussion:

1. A technique is available to describe soil properties in a manner useful to either the vehicle designer or the vehicle customer. The customer can specify his requirements in quantitative rather than qualitative forms, such as "capable of operating in snow, mud, sand, tundra, muskeg, and other adverse soil conditions."

2. Future mobility requirements include:

(a) All vehicles must be air transportable.

(b) All vehicles must be floatable with a swimming capability desired. A means of climbing out of rivers must be developed.

(c) Off-road speed capability must be significantly increased. "Significantly" is considered to be at least a four-fold increase in off-road speed.

(d) Weak soil performance must be improved and design must initiate from the soil-vehicle relationship if the improvement is to be achieved.

(e) Vehicles capable of operation in exceptionally severe environments must be developed for these specific environments.

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